Structural Controls of the Emerson Pass Geothermal System, Washoe County, Nevada

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Keywords

Nevada, Basin and Range, step over, Lake Range, Fox Range, structural controls, exploration, Pyramid Lake, geologic mapping

ABSTRACT

We have conducted a detailed geologic study to better characterize a blind geothermal system in Emerson Pass on the Pyramid Lake Paiute Tribe Reservation, western Nevada. A thermal anomaly was discovered in Emerson Pass by use of 2 m temperature surveys deployed within a structurally favorable setting and proximal to surface features indicative of geothermal activity. The anomaly lies at the western edge of a broad left step at the northeast end of Pyramid Lake between the north- to north-northeast-striking, west-dipping, Fox and Lake Range normal faults. The 2-m temperature surveys have defined a N-S elongate thermal anomaly that has a maximum recorded temperature of ~60°C and resides on a north- to north-northeast-striking fault. Travertine mounds, chalcedonic silica veins, and silica cemented Pleistocene lacustrine gravels in Emerson Pass indicate a robust geothermal system active at the surface in the recent past. Structural complexity and spatial heterogeneities of the strain and stress field have developed in the step-over region, but kinematic data suggest a WNW-trending (~280° azimuth) extension direction. The geothermal system is likely hosted in Emerson Pass as a result of enhanced permeability generated by the intersection of two oppositely dipping, southward terminating north- to north-northwest-striking (Fox Range fault) and north-northeast-striking faults.

Introduction

Blind geothermal systems account for ~35% of geothermal power in Nevada and may represent as much as 2/3 of the geothermal resources in the Great Basin region (Coolbaugh et al., 2006a). Emerson Pass, a blind geothermal system located on the Pyramid Lake Paiute Reservation in northwestern Nevada, was discovered through a 2 m shallow temperature survey. The thermal anomaly was discovered in an effort to identify hidden or blind geothermal resources within the boundaries of the Pyramid Lake Reservation (Pyramid Lake Paiute Tribe, unpublished data; Coolbaugh et al., 2006b; Kratt et al., 2010a). The discovery and subsequent characterization of this system may serve as an example of an exploration framework for other blind systems and further enhance the general understanding of the structural controls of amagmatic geothermal systems in the Basin and Range.

In the Basin and Range, faults generally provide the major conduits for meteoric fluids to circulate to depth, become heated by the elevated geothermal gradient, and return to the near surface as geothermal outflow through the formation and maintenance of fault damage zones and dilational openings (Blackwell, 1983; Curewitz and Karson, 1997; Ferrill and Morris, 2003; Caine et al, 1996; Faulkner, 2010; Faulds et al., 2004a, 2006, 2011a). It is well known that individual fields in the northwestern Great Basin are commonly controlled by moderately to steeply dipping fault zones, particularly north- to north-northeast-striking faults, yet not every fault hosts a geothermal system. Recent investigations have found geothermal systems are commonly hosted at the following structural settings: 1) discrete steps or relay ramps (cf. Larsen, 1988) in normal fault zones, 2) intersections between normal faults and transversely oriented oblique-slip faults, 3) overlapping, oppositely dipping normal fault zones (i.e. accommodation zones; cf., Faulds and Varga, 1998), 4) terminations of major normal faults, and 5) transtensional pull apart zones (Curewitz and Karson, 1997; Faulds et al., 2006, 2011a). High temperature systems in the Great Basin are commonly spatially associated with Holocene faults (Bell and Ramelli, 2007), and permeability of faults is dependent on active seismicity to maintain an open conduit of flow through continual fault slip to minimize healing from mineral deposition (Curewitz and Karson, 1997; Micklethwaite and Cox, 2004; Manga et al., 2012). In addition to favorable structural settings, recognition of common surface manifestations of geothermal systems is also important in locating blind systems. In the absence of hot spring outflow, subtle indicators such as alteration of country rock, silica sinter, tufa towers, or travertine mounds may indicate the presence of a geothermal system that once emanated at the surface but may currently be hidden at depth (Henley, 1985; Simmons and Browne, 2000; Coolbaugh et al., 2009).

High enthalpy systems were recognized on the Pyramid Lake Reservation (e.g., the Needles, Pyramid Rock) in association with tufa towers. Because these sites are culturally sensitive, however, they are not slated for development. An exploration effort using large tufa mounds and shallow-temperature surveys was therefore used as a proxy to identify potentially blind or hidden geothermal resources elsewhere on the reservation (Pyramid Lake Paiute Tribe, unpublished data; Coolbaugh et al., 2006b; Vice, 2008; Faulds et al., 2011b). This strategy led to the discovery of a shallow temperature (2 m probe) anomaly in Emerson Pass near large tufa mounds adjacent to a broad step-over or relay ramp in major normal fault zones (Pyramid Lake Paiute Tribe, unpublished data; Kratt et al., 2010a; Faulds et al., 2011b). In addition, argillic alteration of Miocene rocks and mineralized veins associated with the Packard and Sano Mines, anomalous base metal sulfides detected by a stream and sediment sampling survey (Satkoski and Berg, 1982), and anomalous illite/montmorillonite identified by hyperspectral imagery (Kratt et al., 2010b) indicate a possible hydrothermal system in Emerson Pass.

Tectonic Setting

The Pyramid Lake region is favorable for geothermal development due to its tectonic setting, which has been classified as a major displacement transfer zone (Faulds et al., 2011b). The Walker Lane, a zone of dextral shear accommodating ~20% (1 cm/yr) of the Pacific-North America plate motion (Stewart, 1988; Faulds and Henry, 2008), terminates northwestward in northwestern Nevada and northeastern California, transferring dextral shear into the northwestern Basin and Range (Faulds et al., 2004b, 2012). This results in a broad zone of enhanced west-northwest directed extension in northwestern Nevada, generating elevated levels of dilation and permeability on faults oriented approximately orthogonal to the extension direction (Faulds et al., 2004a, 2005a, 2011b).

Basin and Range extension in northwest Nevada initiated at ~12-11 Ma, followed by a more intense period of extension between ~3.1 and ~2.61 Ma (Trexler et al., 2000; Henry and Perkins, 2001; Colgan et al., 2006; Cashman et al., 2012). Right-lateral faulting associated with the Walker Lane within the Pyramid Lake region began at ~9-3.5 Ma and has accumulated 20-30 km of dextral offset (Faulds et al., 2005a; Faulds and Henry, 2008). Locally, the Pyramid Lake fault, which has accommodated 5-10 km of dextral offset, splays northwestward in the southern part of Pyramid Lake and transfers strain into a system of northerly striking, west-dipping normal faults (Faulds et al., 2005a, 2005b, 2008; Drakos, 2007; Figure 1A). Deformation has been active into the Holocene and late Pleistocene (Anderson and Hawkins, 1984; Briggs and Wesnousky, 2004; Bell and Ramelli, 2007; Vice 2008; dePolo, 2008), and geodetic studies (Kreemer et al., 2009) and earthquake focal mechanisms (Ichinose et al., 2003) indicate that the current principal extensional strain axis trends ~N70Wº-N80W°.

Emerson Pass Geothermal System

Detailed geologic mapping and structural analysis were carried out in the Emerson Pass area to characterize the structural controls the geothermal system. Approximately 204 km^2 were mapped in detail, spanning the west-central Lake Range, southern Fox Range, and the northern Terraced Hills. The stratigraphy was defined in both the Mesozoic basement and overlying Neogene section. Fault, fold, dike, and vein orientations were analyzed to constrain the kinematic evolution of the region and to evaluate the local strain and stress field.

Stratigraphic Framework

The central Lake Range, southern Fox Range, and northern Terraced Hills are composed of Mesozoic metasedimentary rocks, Cretaceous plutonic rocks, Tertiary volcanic and sedimentary rocks, and Quaternary lacustrine sediments, alluvium, and spring deposits (Figure 1B). Tertiary strata rest nonconformably on Mesozoic metamorphic and granitic basement and include ~1.5-2 km of late Oligocene to late Miocene volcanic and sedimentary rocks. The Quaternary units onlap all older rock units. The Mesozoic basement consists of Late Triassic to Early Jurassic metasedimentary rocks (Kinsella, 2010) intruded by Cretaceous plutonic rocks (Bonham and Papke, 1969; Drakos, 2007; Kinsella, 2010).

The Tertiary strata are divided into three principal sequences: 1) Oligocene volcanic rocks, 2) The middle Miocene Pyramid sequence, and 3) a package of late Tertiary sedimentary rocks. Oligocene porphyritic hornblende dacite and coarsely porphyritic andesite crop out in sparse, isolated intrusions or flows and likely correlate with rocks in the northern Lake Range and southern Virginia Mountains (Rhodes, 2011; Faulds et al., 2001; Chris Henry, personal communication, 2012). The middle Miocene Pyramid sequence comprises the majority of the Tertiary section and crops out extensively in the Pyramid Lake region, with well constrained ages between ~16 to 13 Ma (Bonham and Papke, 1969; Faulds et al., 2003; Garside et al., 2003; Drakos, 2007; Vice, 2008; Rhodes, 2011). It consists of multiple flows of complexly interfingering mafic to intermediate lavas, with lesser intercalated clastic sedimentary rocks. Sedimentary strata overlying the Pyramid sequence include late Miocene to Pliocene (?) diatomaceous shale with lesser sandstone and fine silts and sands.

Quaternary sediments onlap older strata and include Pleistocene to Holocene lacustrine deposits of Lake Lahontan and contemporary and historic levels associated with Pyramid Lake, alluvial fan deposits of varying age, recent playa sediment, and hydrothermally altered and indurated rocks associated with the thermal anomaly in Emerson Pass. Tufa and travertine mounds presumably associated with paleo-hot springs and thermal waters (Benson, 1994; Coolbaugh et al., 2009) crop out in three locations. In Emerson Pass a cluster of ~9 tufa mounds stand 5 to 10 m in height, and travertine mounds crop out on southwest flanks of the Fox Range. In the broad alluvial valley between the Terraced Hills and Lake Range, a low lying (~1-3 m) north-trending linear belt of tufa mounds is ~700 m long. The third location is an isolated 5-10 m tall tufa mound ~ 2 km southeast of the tufa lineation.

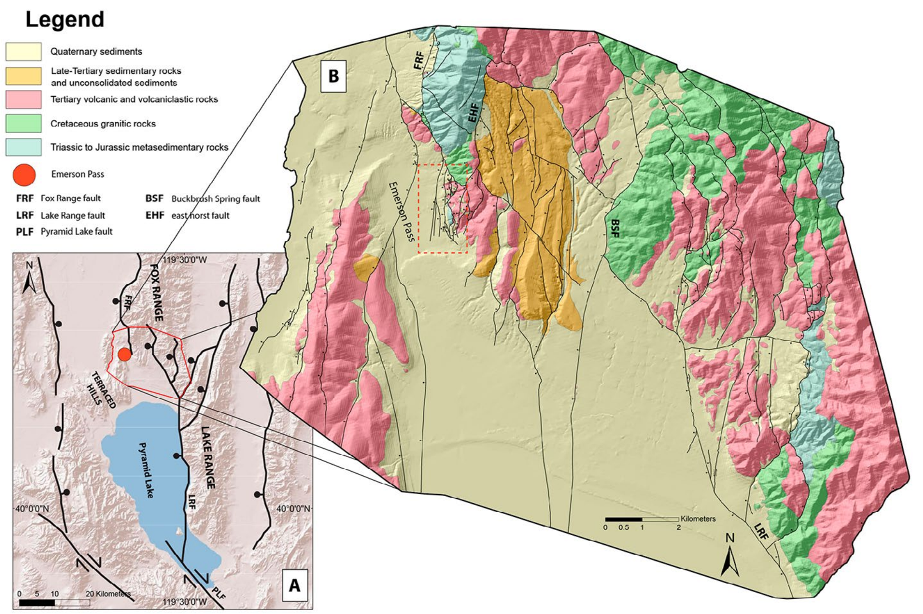

Figure 1. A) Major structures of the Pyramid Lake region. Study area outlined in red. Ball shows the downthrown side for normal faults, and arrows indicate sense of motion for dextral faults. B) Generalized geologic map of the study area. Red dashed box indicates the approximate area of the thermal anomaly and boundary of figure 3.

Structural Framework

The study area lies in a broad left step between the major north- to north-northeast-striking west-dipping normal faults that bound the western flanks of the Lake and Fox Ranges (Figure 1A). These major faults have accommodated several kilometers of slip and tilting of fault blocks to the east (Bonham and Papke, 1969; Drakos, 2007; Rhodes, 2011). Volcanic and sedimentary strata of the Pyramid sequence have tilts of ~30° east, and overlying late Tertiary strata have tilts of ~25° east.

Although the pattern of west-dipping, north- to north-northeast-striking normal faults is generally consistent in the study area, additional structural complexity characterizes the region between the Lake and Fox Range faults. A breached relay ramp (e.g., Larsen, 1988; Peacock and Sanderson, 1994) occupies the left step between the Lake Range and Fox Range faults. The displacement on the Fox Range bounding fault decreases southward in the vicinity of Emerson Pass, where it splays into a series of closely spaced, north-to north-northeast-striking down to the west normal faults. Conversely, displacement on the Lake Range fault decreases to the north breaking into a series of major splays that bound multiple fault blocks. In the westernmost part of the step-over, a major antithetic east-dipping fault bounds a horst block in the southernmost Fox Range, where the Fox Range fault is horse-tailing into multiple splays as it terminates southward. A relatively high density of faults, complex cross-cutting relationships between the west-dipping, horse-tailing Fox Range fault and east-dipping horst fault, and multiple steeply plunging fault intersections are spatially associated with hydrothermal features, such as veining and alteration, in the Emerson Pass area along the southwestern flank of the Fox Range (Figure 3A).

Fault Kinematics

Exposed fault surfaces were analyzed in order to elucidate the kinematics of fault systems and to determine the principal strain and stress axes. Sorting the kinematic data by location demonstrates that the stress and strain fields are spatially heterogeneous (Figure 2A-D) and characterized by a west-northwest-trending (azimuth ~280°, Figure 2B&D) and southwest-trending (azimuth ~227°, Figure 2C) extension direc-

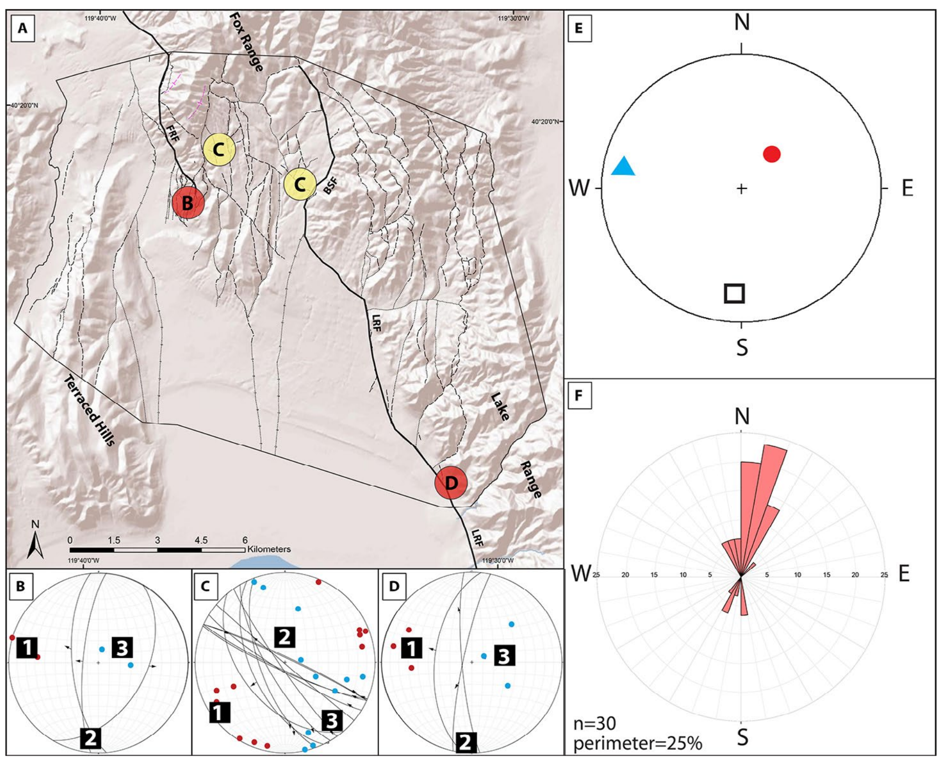

Figure 2. A) Locations where kinematic data were collected. Circles with letters correspond with the kinematic plots below. B-D) Lower hemisphere, equal area stereographic projections of fault planes and strain axes (T-axes=red dots, P-axes=blue dots), and mean principal strain axes (black squares; 1=maximum, 2=intermediate, 3=minimum). B) Strain axes derived from fault slip data from a splay of the Fox Range fault. C) Strain axes derived from fault slip data from within the step-over. D) Strain axes derived from fault slip data from the Lake Range. E) Lower hemisphere, equal area stereographic projection of the principle axes of stress derived from inversion of the spatially sorted data (Blue triangle=minimum stress, red circle=maximum stress, open square=intermediate stress). F) Rose diagram of the strike of vein orientations that cut Miocene volcanic rocks and Quaternary indurated sediments. Radius equals 25% of the data.

tions. The southwest-trending extension direction is limited to the step-over region. The west-northwest-trending (280°) extension direction is compatible with the regional extension direction indicated by focal mechanism solutions (Ichinose et al., 2003), geodetic data (Kreemer et al., 2009), nearby geologic data (Rhodes, 2011), and preliminary borehole breakout data from nearby Astor Pass (David McNamara, personal communication, 2013). Veins that cut Miocene volcanic rocks and indurated Quaternary sedimentary rocks directly east of the thermal anomaly strike predominantly north-northeast (Figure 2F), indicating a recent west-northwest-trending extension direction in the Emerson Pass area. Therefore, the west-northwest-trending extension direction is used for conceptual models of the Emerson Pass system (Figure 2E).

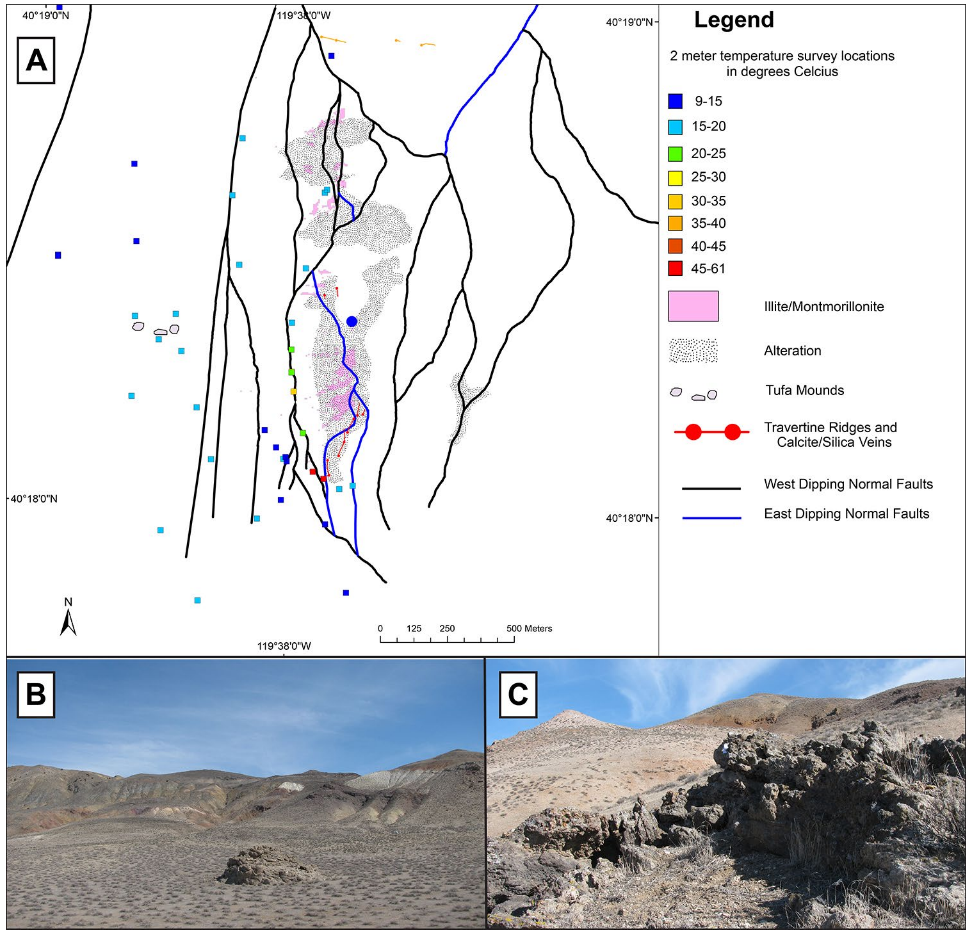

Figure 3. A) Map of Emerson Pass showing faults, surficial features related to the thermal anomaly, and the locations of 2 m probe temperature measurements. B) View of Emerson Pass looking northeast toward the southwest flank of the Fox Range with a tufa mound in the foreground and altered Mesozoic and Miocene rocks on the hillside in the background. C) View looking north at the southern end of Emerson Pass at a travertine ridge showing subvertical and subhorizontal layering with altered Mesozoic slate and Miocene volcanic rock in the background.

The Geothermal System

Tufa mounds, alteration of Miocene volcanic rocks, mineralized veins, alteration, and a shallow temperature anomaly suggest a geothermal system in the Emerson Pass area (Satkoski and Berg, 1982; Pyramid Lake Paiute Tribe, unpublished data; Kratt et al., 2010a, 2010b). Additional geothermal features indicative of a high temperature system, including travertine mounds and calcite/silica veins (Figure 3C), were discovered in this study. Altered Miocene and Mesozoic rocks crop out in Emerson Pass primarily on the hillside to the east of the temperature anomaly. The alteration has an elongate N-S trend ~1.5 km in length and occurs in tuffaceous sedimentary rocks, aphanitic andesitic volcanic rocks, and Mesozoic slate. It includes bleaching and oxidation of the country rock, silica/calcite flooding, disseminated pyrite and jarosite in the volcanic rocks, and anomalous illite/ montmorillonite, as indicated by hyperspectral imagery (Kratt et al., 2010b; Figure 3B). The veins consist of interlayered calcite and chalcedony, cut Mesozoic, Miocene, and Quaternary units, and appear to have issued out at the surface in the past, as evident by apparent travertine ridges with subhorizontal layering above sub-vertical veins (Figure 3C). The travertine mounds and calcite/silica veins strike north-northeast and dip steeply to the east and west. Calcite and silica cemented lacustrine gravels crop out proximal to these veins. The cemented sediments form subhorizontal, resistant ledges that rest nonconformably on Mesozoic slate and Miocene andesite.

A series of 2 m shallow temperature surveys showed a heat anomaly (maximum temperature variably from 60.1°C to 83.3°C) along the eastern margin of Emerson Pass (Kratt et al., 2010a; Pyramid Lake Paiute Tribe, unpublished data-D. Noel, personal communication, 2012; Shevenell and Zehner, this volume). This anomaly is ~1.25 km long and elongate along a north-striking, down to the west fault, which is a splay of the range-front fault bounding the Fox Range. A maximum recorded temperature of 35.1°C was measured in the original temperature survey (Kratt et al., 2010a), but even higher temperatures (83.3° C) were discovered in a 2012 survey conducted by the Pyramid Lake Paiute Tribe (D. Noel, personal communication, 2012). A final survey was conducted in 2013 to confirm the anomaly (measured and revised to 60.1°C in March 2013) and normalize temperature data to the original survey (Shevenell and Zehner, this volume; Figure 3A).

Discussion and Conclusions

Detailed geologic mapping and structural analysis provide insight into the structural controls of a blind geothermal system in the Emerson Pass area. The 2 m temperature surveys and geologic mapping demonstrate that the system is active today in the subsurface and was likely active at the surface as recently as the late Holocene. In addition, temperatures of ~60° C at only 2 m depth and the presence of chalcedony at the surface indicate a robust geothermal system. The Emerson Pass thermal anomaly lies adjacent to a broad step-over, within the southward termination of a major range-front fault, and at an intersection between major oppositely dipping faults. This structural complexity and a nexus of faults has generated a zone of high fracture density and thus enhanced permeability. Structural analysis revealed a west-northwest-trending extension direction in Emerson Pass under a normal faulting regime. Thus, geothermal systems in the area are likely hosted by north- to north-northeast- to north-northwest-striking normal faults. Accordingly, the heat anomaly resides on a north- to north-northeast-striking normal fault. Based on the geologic data, shallow temperature surveys, and conceptual model, it is recommended that temperature gradient well sites be placed ~60-160 m west of the west-dipping, southward terminating splay of the Fox Range normal fault proximal to its intersection with the antithetic east-dipping normal fault.

The discovery and subsequent characterization of the Emerson Pass thermal anomaly provides a good example of a grassroots approach to geothermal exploration (see Hinz et al., (this volume) for a more detailed exploration workflow). The approach may vary from system to system, but for Emerson Pass it included: 1) exploring in a region of broad transtension, 2) recognizing surface features indicative of geothermal activity in a structurally favorable setting (e.g., tufa mounds in a broad step-over), 3) deployment of shallow temperature surveys proximal to such features, 4) detailed geologic mapping and structural analysis of a broad region surrounding the exploration target, 5) additional temperature survey efforts based on detailed mapping and previous surveys, 6) development of a conceptual model for the geothermal system, and 7) siting of temperature gradient wells to further characterize the system. The results from the final step will dictate if the project should move forward. Subsequent steps should work to constrain and model the subsurface to target production wells. The general work flow and findings of this study may contribute to developing a framework for the exploration of blind geothermal systems elsewhere on the Pyramid Lake Paiute Reservation and throughout the Great Basin.

Acknowledgments

We wish to express our appreciation to the Pyramid Lake Paiute Tribe for allowing continuing research and access to their land for field work. This work was supported by an American Recovery and Reinvestment Act grant from the Department of Energy (EE0002842) and awarded to the Pyramid Lake Paiute Tribe. We thank Donna Noel for facilitating much of this research.

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